

Common Factors Contributing to Vehicle Body Painting Defects in Automotive Body Repair and Painting Garages: An Application of the 4M1E Framework

Gebremedhin Girmay Aregawi^{1*}, Zhongmin Wang¹, Wenping Zhao²

¹School of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin, China

²School of Vocational Education, Tianjin University of Technology and Education, Tianjin, China

Email: *gebreg19@gmail.com

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Abstract

Vehicle body painting is the most important issue in the final stage of the automobile maintenance process, and it is related to the appearance, rust-proofing, and value of the vehicle. Yet, achieving a deficiency-free finish is challenging in less developed regions. In the current research, the basic principles of some abnormal entities, including orange peel, blistering, and fish-eye defects, found in the automotive garages of Addis Ababa, Ethiopia, are studied using the 4M1E construct. We employed mixed methods, involving cross-sectional surveys of 31 technicians and supervisors from eight purposively sampled garages, along with physical panel inspections and a small-scale intervention trial. Data were processed using IBM SPSS Statistics (Version 27) and included descriptive statistics, reliability analyses, and multiple regression analysis modeling. The study found that lack of infrastructure integrity and process standardization were the main contributors to defects. The only major issue found was the disturbing absence of environmental management, as 58.1% of the garages were operating without a spray booth. This was then compounded by inconsistent processes, including a lack of a uniform paint mixing guide and insufficient flash-off time. It is shown that the quality of the paint is extremely deteriorated due to the failure correlation along the 4M1E domain. It can be inferred that significant quality improvements can be realized if investments are directed towards basic infrastructure and the introduction of simple standard operating procedures, as well as training for technicians. This research provides a validated diagnosis and practical, low-cost intervention for automotive garages in the emerging industry, enhancing quality, reducing rework, and improving economic sustainability.

Keywords

Automotive Painting Defects, 4M1E Framework, Vehicle Body Repair, Paint Quality, Spray Painting

1. Background of the Study

Remarkable progress has occurred in the automotive painting industry due to the development of the technology employed for materials and processes from the 1900s to the present. Early painting techniques (from 1900 to 1950) involved air-drying paints and sanding between coats, followed by polishing and polishing until the entire piece was ready to work on for weeks. All painting processes were carried out manually. The combination of numerous reasons to continually improve speed has led to remarkable developments over the past century. The introduction of mass production required faster curing paints, improved film performance in terms of corrosion and durability of colours, greater environmental compliance, and fully automated processes for reliability, which were represented by crucial milestones (Streitberger, 2008).

Quality and environmental concerns have been driving vehicle painting procedures for many years. In general, very high product quality and stability of the processes may be achieved. The processes are already changing dramatically due to new customer requirements, new material developments, new substrates, and new cost challenges, and will most likely have to change even more and over a larger portion of the total process volume in the medium/long-term (Corbu et al., 2024).

In the luxury goods or automotive market, visual appearance and color are critical. The new automotive colors and trends are dictating the 1st product in this revolutionary coating. Especially in the sector of high-quality motor vehicles, regardless of the cause, sale, or accident, a car may need a repair of a certain part or area, disguising the repair is required so that it may not be visible to the client, depending on the colour formula adopted. No matter what methods are used for repair, a color difference would exist between the initial dye and the formula derived by the colorimeter (Hilt, 2011).

Vehicle body painting protective coating application to prevent rust and wear, and beautify the body's appearance. Using the 4M1E model for this stage reveals several failure points: human factors accommodate workers' skill and workload (with long periods of work or heavy work, errors can occur); machine factors include the stability of painting equipment and oven/dry systems both are essential to achieve uniform quality and the desired film property; material factors are related to the paints and electrophoretic solution's properties, as their chemical and physical state contributes to the capability and finish of a coating; method factors are related to the process to be performed, such as painting conditions and technical details, which should strictly follow standard procedures to avoid sagging

and orange-peel; and environment factors are concerned with proper temperature and humidity with a dust-free environment that can lead to paint booth cleanliness, as contaminations or improper settings can significantly affect the resistance and durability coating (Xiang et al., 2025).

Growth in customer expectations for car appearance means that the automotive paint shops have to inspect every car body thoroughly. According to present practice, manual personnel visually check every car body for finding and rectifying bondo sags. But the blemish may not be perceivable and may not be judged objectively and consistently by humans over a period of time. After they are detected, a robust classifier is required in order to obtain more detailed information regarding the paint defects. The dating can be used to develop the painting process and to determine who caused the painting defects when the defect classification is in operation. Thus, the quality control circuit is shortened, and the surface quality of various colour formulas is objectively investigable as to their formulation. It can be counteracted for a predetermined number of defect types (Kieselbach et al., 2019).

2. Literature Review

2.1. Automotive Coatings and Topcoats

Coatings for automotive surfaces are on the leading edge of technologies that can create durable surfaces that are both aesthetically pleasing, exceeding customer appearance expectations, and drive efficiency and environmental benefits due to regulations. These achievements are built on 100 years of experience, trial and error application of techniques and technology, and theoretical analysis. As a result of research focusing on the how, why, when, and where of automotive coatings, the work done in the area of droplet and deposition control, and the emergence of new technologies and paint chemistries, an overview of this subject would be of use to industrial practitioners and to researchers. In general, the key performance attributes that are forcing advancement in automotive painting technologies are:

- A. Surface appearance and finish.
- B. Anti-corrosion performance.
- C. Suitable for mass production.
- D. Cost-effectiveness and sustainability.
- E. Durability and aesthetic longevity (Akafuah et al., 2016).

The well-painted body of a vehicle is worth more to customers because of its physical appearance. Highly attractive paint color from the paint mixing procedure is one of the production mechanisms for making any exterior surfaces, such as those used by painting industries or vehicle body repair companies. In low-income industrialized countries such as Ethiopia, a standardized vehicle body paint mixing machine is not available. Commonly, vehicle body repair and painters in other vehicle repair business types and garages mix paints by their own hands without the help of others, which is called a manual vehicle body paint mixing

operation. However, such a hand-mixing operation has many drawbacks, such as unmarketable paint, low painting quality, and non-resistance to solar and rain, causing a decline in the product value. While mixing was going on, the skin of their hands became affected due to the paint's chemicals, and their breathing system was affected due to the smell of the paint. This took longer during the mixing process, but it has mixed paint with slight non-uniformity (Musabyimana & Turabimana, 2021).

2.2. Vehicle Body Is Painted to Fulfill the Following Primary Functions

Low-level features, including symmetry, curvature, and colour, the appreciation of which represents some of the earliest forms of aesthetic experience for people, have been an old subject of interest in the psychology of art and aesthetics. Recent work in this tradition shows that people indeed consider glossy, shiny objects and materials as more attractive than flat, matte ones. In addition to single factors such as glossiness, glossy was a between-person manipulated factor, concurrently varying with techniques that controlled for factors, such as weight, color quality, and resolution. There was some evidence of (weak) replication in ratings of attractiveness. Participants rated the glossy images as sexier than the matte ones, but the difference was slight and not statistically significant. Implied attractiveness ratings were substantially moderated by individual differences in the aesthetic appreciation aspect of openness to experience. However, when aesthetic appreciation was high, participants found the images attractive regardless of condition. When it was low, they had a significant preference for the glossy pictures over the matte ones (showing the classical glossiness effect) (Silvia et al., 2021).

2.2.1. Aesthetics and First Impressions

Vehicle painting mainly appears for aesthetic purposes. This also applies to the application of composite materials for complicated designs that offer visual appeal and functional style. As art and an everyday experience, cars offer aesthetic experiences. This is a significant part of car design that affects clients' insight and enjoyment. A well-kept, popular color can increase curb appeal and attract buyers more promptly. Well-maintained paint (no mismatched color, no dullness, no significant scuffs, chips, or fading, and not too many other artificial-looking polishes or waxes) tells buyers your car was treated properly and reduces the perceived risk. A damaged or mismatched panel, a deep scratch in the paint, hidden rust beneath the paint, or peeling clearcoat are all things that diminish value for needed repairs (Silvia et al., 2018).

The color of modern lacquer painting is another remarkable visual beauty. The pigments of lacquer painting are usually highly saturated and glossy, so the colors appear more brilliant and more dazzling. Artists come up with a surprising array of visual effects with clever uses of color. In the realm of contemporary fine art, lacquer painting has appealed to a number of artists who applied their creative ideas to the singular material and process. Lacquer painting has introduced a new

type of expression in artistic creation and presented viewers with a brand-new visual experience. Colour is one of the key instinctive features of the visual arts, and has a vital influence on expressive capacity. As with popular wood handi-crafts, the space of colored play is also enriched by modern painting, which utilizes chosen colors and the world of color to create visual effects (Chen, 2023).

2.2.2. Corrosion Protection (Primer and Lacquer Coat)

One of the primary uses of automotive body paint is to provide the vehicle with long-term corrosion protection of the metal surface (typically steel or aluminum). Vehicles are often subjected to environmental damage, including water, road salts, industrial pollutants, and extreme temperatures, which induce electrochemical corrosion of vehicle bodies. Modern paint coatings ensure protection from corrosion through a multi-layer system.

- Pre-treatment (Zinc Coat): Enables superior adhesion and serves as a passive anti-corrosive layer for protection against corrosion prior to application of paint on the coil.
- Primer (Epoxy Primer): Is the first defense and mainly is used in corrosion-prevention (Zinc phosphate), where it contains inhibitive pigments which, on chemical reaction, neutralize the oxidation agents.
- Basecoat: Adds color, more UV resistance, and is less critical for corrosion prevention.
- Clearcoat: Serves as a protective layer over the base paint to minimize scratches and prevent erosion of the underlying paint and metal.

In the last 10 years, had been possible to find technologies such as the self-healing coatings (polymeric coatings with micro-capsules) and the galvanization (coatings based in layer rich in zinc) that enables to push over the 4 days the lifetime to the moment to start the corrosion, corroborating, therefore that these coatings are efficient and have durability requested in the automotive field.

2.2.3. Surface Protection

A paint of a car body must have surface protection against mechanical, chemical, and environmental influences. Modern multi-layer paintwork serves the purpose of covering degradative substances while respecting the car's aesthetics. Key protective roles include:

Strength and scratch resistance: The clearcoat (typically polyurethane or acrylic) is the top layer that includes hardeners to prevent scratches from minor impacts, washing, and dust (Deflorian et al., 2006).

Resistant to stone chips: Limpet coating has a more elastic primer, which absorbs the energy of impact, preventing the crack from migrating to the steel (Mohanty et al., 2023).

2.3. Factors Influencing the Quality of Automotive Body Painting

2.3.1. Surface Preparation

Surface pre-treatment and ablation/removal of the old (damaged) varnish film in

a vehicle body shop, and their effect on the corrosion resistance of the vehicle body material. One method of preparing a surface was the conventional practice of sanding the surface of metal sheets with sandpaper. Automobile refinishers primarily employ this technique. Soda pressure blasting was introduced in the 1970s, and this method is particularly suitable for removing paint from soft substrates such as masonry. Other, more innovative methods included abrasive blasting (using sand) with powder made of ground-up plastic. All tests were performed in order to find the best way of preparing the car body sheet surface, mainly in order to keep the most significant quantity of zinc—protective layer over zinc used to prevent steel corrosion. Among the reasons for insufficient surface pre-treatment are incorrect cleaning, insufficient sanding, and ineffective degreasing (Ulbrich et al., 2021).

2.3.2. Conditions of the Surrounding Environment

Automotive painting quality and efficiency are greatly influenced by environmental impacts, especially humidity and weather. Excessive humidity may not only result in slow paint drying, but also might cause moisture retention (blushing or haziness) and ultimately poor adhesion from surface condensation. On the other hand, low humidity, if the latter is too low, could lead to too fast a solvent evaporation so that there exists the likelihood of an orange peel or dry spray texture. Temperature variations also complicate the application of the inks by changing the viscosity, atomization, and compatibility characteristics of the painting substrate. Workplace standards suggest that relative humidity in a controlled spray booth should be between 50% and 70%, and that temperatures should be between 20°C and 25°C, to minimize these problems. Recent developments involve humidity-resistant paint systems and infrared curing systems to take into account climatic issues. However, differences in regional climate, including tropical/open versus arid, remain relatively unexplored, and this presents a gap in adaptive painting for a variety of unique environments (Ogrean & Moldovan, 2024).

2.3.3. Paint Application Process

Paint application in the automotive industry is a closely monitored, multistage industrial process to guarantee the performance, protect the beauty, and prevent the corrosion of topcoats. It starts with a pre-treatment of the metal surface to ensure paint adhesion and rust prevention. The raw metal is cleaned, degreased, and phosphated. Subsequently, an electrode position primer is electro-phoretically deposited and then baked to produce a smooth, corrosion-resistant primer coat. A primer surfacer is then sprayed onto the fill surface irregularities, then the basecoat, or color layer, is robotically-applied, usually containing metallic or pearlescent pigments for cosmetic appeal. At the end, to finish, a clearcoat is baked on for gloss, UV shielding, and protection against scratches, and a clearcoat is cured in ovens at high temperatures so the hardness level is reached. Sophisticated quality control features, including automated defect inspection and thickness testing, meet the tightest industry standards. Latest developments are found in waterborne

coatings, powder clearcoats, and smart manufacturing towards lowering environmental impact and increasing efficiency (Pendar et al., 2022).

2.4. Common Paint Defects in Automotive Body Shop Painting

Some of the issues or problems, and the causes of the issues or problems, that may be associated with primer surfacers and topcoats are (Akafuah et al., 2016):

- Orange peel: The surface resembles an orange peel.
Cause: Nozzle held at too far distance from surface or shop temperature is too high (best results achieved at 65°F to 75°F); clogged spray nozzle.
- Blistering: Bubbling, pitting, or swelling.
Causes: Solvents, dirt, or moisture trapped on the paint coating; rust under the surface.
- Mottle: Appearance of irregularity (usually pertains to metal finishes).
Causes: Insufficiently stirred paint; spray nozzle too close to the surface being sprayed; too hot or too cold surface.
- Fish eyes: Little fish eyes in the finish.
Causes: Surface was not adequately cleaned (e.g., surface was greasy or silicone remnants on the surface).
- Floating or wrinkling: An expanded or wet film.
Causes: Improper drying of the previous coat; lacquer coat sprayed over enamel.
- Runs/sags: Paint is not sticking or/adequately covering properly.
Causes: Drying of paint too slow, etc., paint sprayed over wax or oil or greasy surfaces; undercoats too slick and glossy, overcoating too soon; weather too hot or too cold.
- Dry spatter: Paint dust settling on a painted area.
Causes: Too fast or too slow paint spray—the peak of the sprayer is too far away from the surface.

To meet the customer's requirements and to follow the competition in the market, it is essential for any manufacturing organization to reduce rejection.

A priori ranking of influencing the quality of car body is the most critical factors makes: incorrectness of the used paints, varnishes or solvent; contamination of the compressed air and paints, varnishes; incorrect viscosity of the paints, varnishes; preparing of the paints, varnishes on insufficiently surface; unsatisfactory purity of the room of the painting and drying chamber; not sufficiently stirred up paints, varnishes; absence of correspondence of pressure of the compressed air, and absence of correspondence of supply material. When monitoring the paint and varnish coating, the comparison of the repair values of the paint and varnish coating thickness with the factory ones needs to be carried out; the deviation must not exceed 10% - 15% (Khasanov et al., 2019).

3. Methodology

The method was a mixed, multi-site field study to explore the factors behind automotive paint defects in vehicle painting garages in Ethiopia. The trial was de-

signed as a cross-sectional diagnostic survey with a small intervention. Observation of a series of cross-sectional investigations permitted the identification of determinants of paint defects under ordinary working conditions, and, during an intervention phase of brief duration, it was explored whether easy and low-cost improvements of the process would lower paint defect prevalence.

Brief surveys, using (1: Strongly Disagree, SD), (2: Disagree, D), (3: Neutral), (4: Agree, A), and (5: Strongly Agree, SA) as a Likert-scale, 13 quantitative and 2 qualitative questionnaires were sent out to participants to collect data on training, safety practices, equipment maintenance, type of paint brands, and frequency of rework to found the most common (high/low) number of cars (painting jobs) rework.

Following Li's framework (Li, 2013), the Likert scale responses were assigned categorical weights, which are presented in **Table 1**.

Table 1. Likert scale's categorical weight.

S/n	Scale	Range Value	Description: $5 - 1 = 4$, then $(\frac{4}{5} = 0.8)$
1	Strongly Disagree	1 to 1.80	1 to $1 + 0.8$
2	Disagree	1.81 to 2.60	1.81 to $1.8 + 0.8$
3	Neutral	2.61 to 3.40	2.61 to $2.6 + 0.8$
4	Agree	3.41 to 4.20	3.41 to $3.40 + 0.8$
5	Strongly Agree	4.21 to 5.00	4.21 to $4.20 + 0.8$

The research was limited to automotive body repair and painting garages in Addis Ababa. Purposefully sampled, eight garages were split into two lower, four middle, and two upper-grade categories. The pre-classification descriptors included technician competency and education, tools and equipment type and level, and service range. Within these pre-classified garages, purposively sampled individual participants were selected based on the study's inclusion criteria.

Eight painted panels were randomly selected in each garage to reach a minimum of 120 observations as required for adequate statistical power. The 4M1E (Man, Machine, Material, Method, and Environment) framework was employed to categorize the contributing factors. And 31 qualified respondents (10 supervisory and 21 painters) with work experience of five years and above, and all of whom were male technicians, participated in the survey. The variables were classified as dependent and independent variables.

Variable Mapping to the 4M1E Framework:

Independent variables were crafted to probe the root causes of paint defects and were systematically ordered and classified per the 4M1E framework. This is illustrated in **Table 2**, which shows a description of each survey item.

Table 2. Mapping of independent variables to the 4M1E framework.

4M1E Category	Independent Variable (Survey Item)	Descriptions
Man	“I have been trained on methods of paint application.”	✓ Evaluates skill and knowledge.
Machine	“Serviced or cleaned spray gun.”	✓ Following up on equipment maintenance.
	“Your shop has a spray booth.”	✓ Core of environmental control infrastructure.
	“I use a water trap or an air dryer on the compressor line.”	✓ Measures and controls the quality of the compressed air supply.
Material	“I did not notice paint problems caused by poor thinner or low-quality paint.”	✓ Proxies the perceived quality of paint and solvent inputs.
Method	“I consult mixing ratio and viscosity tables/manuals.”	✓ Examines the adherence to standardized mixing procedures.
	“I allow proper flash time between coats.”	✓ Assesses compliance with recommended application techniques.
Environment	This category is primarily captured by the “spray booth” variable under Machine, as the booth’s purpose is to create a controlled environment.	✓ The absence of a booth constitutes an environmental deficiency.

Note: Dependent variables consisted of frequencies of specific paint defects reported by interviewees, which indicate outcomes resulting from the 4M1E factors.

All the elements of the 4M1E framework had at least one measurable variable. For example, the “Man” component was evaluated through formal training, while “Method” was assessed through adherence to the mixing guides and the flash-off times. The “Machine” and “Environment” factors are interrelated, as the spray booth and air dryer are the key machines that directly establish the controlled quality of the painting climate. This allowed the study to cover the impacts of one domain that contributes to the prevalence of paint defects.”

The qualitative questions, such as the following, were asked:

1) In your opinion, what is the number one reason for auto paint problems in your garage?

2) What kind of gun do you often use? Such as Traditional HVLP (High Volume Low Pressure).

Procedure in-formation: structured observation. The observational checklist was used as a guide to observe those process variables related to each coated plank. Some environmental conditions (temperature, humidity, air current, dust index) were also monitored.

Each panel was then visually inspected for gross defects after 24 - 48 hours of cure time (accompanied by a photo atlas for comparison).

In the Intervention Phase at two selected garages, a low-cost intervention package was implemented, consisting of:

- Uniform mixing ratio and viscosity references.
- Spray-gun set up posters and technique.
- Daily booth cleaning procedures and compressor draining schedules.

- Flash-time and baking.
- Incident rates and quality measures before and after intervention were compared to the rate of defects and quality measures in garages simply practicing as usual.
- Analysis of Data: The data collected were entered into SPSS for analysis.
- Defect prevalence, film thickness, gloss, and adhesion were described by means.
- Observers were trained with defect images and test scoring trials.

4. Result and Discussion

The information was screened and coded by IBM SPSS Statistics version 27 and statistically analyzed. We performed a mode, median, frequency, and standard deviation in the Cronbach's alpha test, a regression model estimated by maximum likelihood, and robust standard errors. Descriptive statistics of all outcomes are presented in **Table 3**, **Table 4**, and **Table 5**.

As a reference from this idea (Tavakol & Dennick, 2011), " $\alpha \geq 0.9 =$ Excellent, $0.8 \leq \alpha < 0.9 =$ Good, $0.7 \leq \alpha < 0.8 =$ Acceptable, $0.6 \leq \alpha < 0.7 =$ Questionable, and $\alpha < 0.6 =$ Poor". We conducted the reliability or Cronbach's alpha test, and the result is 0.963, which is an excellent internal consistency, and the answers to the questionnaire were reliable.

Table 3. The frequencies, means, mode, and standard deviations of each item.

Variables (Dependent and Independent)	Valid	Missed	Mean	Mode	Std.D
1. I received formal training in spray-painting techniques.	31	0	3.1	3	1.248
2. I use any reference charts/manuals for mixing ratios and viscosity.	31	0	2.84	2	0.934
3. The spray gun is cleaned or serviced.	31	0	3.42	3	0.720
4. Your garage uses a spray booth.	31	0	2.68	1	2.006
5. I use an air dryer or water trap on the compressor line.	31	0	3.10	3	0.790
6. I did not notice paint problems caused by poor thinner or low-quality paint.	31	0	3.00	2	1.238
7. I allow proper flash time between coats.	31	0	2.90	3	0.746
8. I did not often experience orange peel defects.	31	0	2.77	2	0.956
9. I did not often experience runs/sags.	31	0	2.87	3	0.846
10. I did not often experience fish eyes.	31	0	2.97	2	0.836
11. I did not often experience blistering.	31	0	2.81	3	0.654
12. I did not often experience mottling.	31	0	3.00	3	0.730
13. I did not experience paint defects linked to a power failure.	31	0	3.19	3	0.980

From **Table 3**, the grand mean is the summation of all the individual means divided by the number of variables. That is, $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$, where, \bar{x} = Grand mean, $\sum_{i=1}^n x_i$ = the summation of all means (x_1, x_2, \dots, x_n) and n = Total

number of means.

$$x = \frac{38.65}{13} = 2.97$$

This finding indicates that the respondents perceive little on the items whose means are lower than the grand mean (2.97) and perceive a lot on the items whose values are higher than the grand mean.

The descriptive statistics, in general, the survey paint quality and process control were rated negatively by the surveyed garages; the grand mean of 2.97 was less than the neutral midpoint. The most significant weakness noted is the acute absence of spray booths, which also had the lowest average (2.68) and highest standard deviation, revealing a severe resulting polarizing infrastructure deficiency. This is combined with a general lack of standard mixing guides (mean 2.84) and mediocre scores regarding formal training (mean 3.1). These deficiencies manifest themselves quite directly as simple defects, all of which are considerably utilized, including orange peel (2.77) and blistering (2.81). As a result, these defects will commonly occur. Spray gun maintenance was a good adherence factor in the study, as it had the highest mean score (3.42) and the smallest range, indicating a more homogeneous use of that procedure.

Table 4. Percentage frequency of the response.

Variables	SDA Freq.	DA Freq.	N Freq.	A Freq.	SA Freq.
1. I received formal training in spray-painting techniques.	3/9.7%	7/22.6%	11/3.5	4/12.9%	6/19.4%
2. I use reference charts/manuals for mixing ratios and viscosity.	1/3.2%	12/38.7%	10/32.3%	7/22.6%	1/3.2%
3. The spray gun is cleaned or serviced.	0/0%	2/6.5%	16/51.6%	11/35.5%	2/6.5%
4. Your garage uses a spray booth.	18/58.1%	0/0%	0/0%	0/0%	13/41.9%
5. I use an air dryer or water trap on the compressor line.	0/0%	8/25.8%	10/32.3%	3/9.7%	10/32.3%
6. I did not notice paint problems caused by poor thinner or low-quality paint.	3/9.7%	9/29.0%	9/29.6%	5/16.1%	5/16.1%
7. I allow proper flash time between coats.	0/0%	10/32.3%	14/45.2%	7/22.6%	0/0%
8. I did not often experience orange peel defects.	2/6.5%	12/38.7%	8/25.8%	9/29.0%	0/0%
9. I did not often experience runs/sags.	1/3.2%	10/32.3%	12/38.7%	8/25.8%	0/0%
10. I did not often experience fish eyes.	0/0%	11/35.5%	10/32.3%	10/32.3%	0/0%
11. I did not often experience blistering.	0/0%	10/32.3%	12/38.7%	9/29.0%	0/7.1%
12. I did not often experience mottling.	0/0%	10/32.3%	12/38.7%	9/29.0%	1/7.1%
13. I did not experience paint defects linked to a power failure.	0/0%	9/29.0%	10/32.3%	9/29.5	3/9.7%

The narrative is strikingly illustrated in the frequency distributions in **Table 4**, which reveal a comprehensive divide of practices. The question about the spray booth is an excellent example of this; 58.1% of respondents strongly disagreed

with using one, and 41.9% agreed, so we have a split garage, those with and those without suitable environmental controls. And, just over 41.9% disagree that they consult reference books to help them mix, demonstrating that a high proportion are guessing work. The respondents are also split on training, with 32.3% agreeing and 32.3% disagreeing that they have had this, and a large proportion of neutral respondents who indicated that any training they had may be insufficient. As a result, if we understand the loosening because of the low quality parts, almost 50% of the sample we have speeches about showing orange peel defects.

The interview response revealed three primary ideas that indicate the common defect in paint quality.

Incorrect paint mixture proportions. Many participants identified inconsistent defect proportions in the paint mixture as the primary reason for the queried defects. This rationale was also noted in the literature, which described how the mixture proportions influence paint adherence, gloss, and other defect-free outcomes. Many respondents cited the problem of estimating the ratio and having confidence in their guess, rather than measuring it accurately.

In terms of paint preparation, one respondent from a low-level garage said, “We usually prepare the paint materials by eye/trial and error. If it becomes thick, we add more reducer and vice versa, and sometimes the final result is inaccurate, which causes paint defects.”

This points to the result of the absence of laid-down procedures centered on the paint order, and the specification checklist with the negative use of informal methods when it comes to paint preparation, which in turn, relates to the informal works done and the poor finishing of the paint.

In relation to the Painting Techniques, the issues centered on the spray distance, speed, angle, overlap, and other factors that will lead to poor paint finishing. One supervisor said about the imbalances in the skills of the paint crew, “Most of the painters do not follow the correct or uniform painting parameters, and it is a bit hard to train them,” still speaks.

To carry out the work, one of the respondents said, “Tools and equipment, especially spray guns and compressors...” It is conclusive to resolve that the outcome will be of poor quality when the work tools and equipment, such as spray guns and compressors, are of poor quality.

Regression analysis

Taking “I did not frequently encounter orange peel defects” as a dependent and all the independent variables, the outcome is shown as in **Table 5**.

Table 5. Regression analysis.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.910 ^a	0.828	0.785	0.444

R = 0.910. This is the correlation between predicted and measured values for the dependent variable.

This is what an influential positive association looks like: predictors do a great

job at jointly explaining the outcome.

R Square = 0.828 (82.8%): What this means is that 82.8% of the variation we observe in the dependent variable only takes the form it does because of our set of independent variables (training, flash time, spray gun maintenance, booth, air dryer, manuals). This seems to hold excellent, even 40 to 60% for social/ field studies is usually considered good.

Std. Error of the Estimate 0.44. This represents the average distance of the observed values from our fit. Lower values indicate more accurate predictions, and 0.444 is definitely low, which means a good model fit.

Table 6. ANOVA test.

Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	22.697	6	3.783	19.227	0.000 ^b
Residual	4.722	24	0.197		
Total	27.419	30			

Interpretation: The predictors (training, booth use, flash time, etc.) explained a big part of the variance of the DV. That is, our model is not just fitting by hand-waving; it is doing so at a statistically significant level. ANOVA ($F = 19.227$, $p < 0.001$). Model: Following the methodology of Field (2024), the model is highly significant overall ($p < 0.001$). We used the same methodology on each dependent/independent variable, and they are all significant, as detailed in Table 6.

4.1. Intervention Trial Results

A low-cost intervention package was implemented at two purposefully selected garages (one moderate-level garage and one low-level garage) to test a practical solution and validate the identified root causes. The intervention described in the methodology involved the introduction of standard mixing guides, the display of spray-gun setup posters, and the enforcement of flash-off times.

Defect rates were assessed for the week prior to the intervention and the week following it. The summary results showed significant improvements in the quality of painting, which is detailed in Table 7.

Table 7. Comparison of defect prevalence before and after intervention in two low-level garages.

Type of Defect	Gar. X (Before Intervention)	Gar. X (After Intervention)	Gar. Y (Before Intervention)	Gar. Y (After Intervention)
Orange peel	45%	12%	55%	24%
Runs/sags	25%	10%	32%	9%
Fish eyes	20%	5%	24%	9%
Blistering	7%	2%	14%	4%
Overall defect	24.25%	7.75%	31.25%	11.5%

Note: The defect rate is the percentage of the inspected panels that are found with a defect.

As can be seen, the simple, low-cost intervention provided was very effective in reducing the overall defect rate by 68% in garage X and by 63% in garage Y. The most significant improvements were in orange peel and fish eyes, which are defects resulting from improper mixing and application techniques. These defects were the most focused on during the intervention. The results from this trial support the conclusion of the study: that the standardization of processes with minimal instruction to technicians can produce significant improvements, and this is something that can be implemented right away.

4.2. Study Limitations

This study has shortcomings. Along with the insights this study offers concerning the impacts on the paint defects found on garages within Addis Ababa, the advances of this study have to be taken with the mentioned shortcomings. With only 31 participants from eight garages, the sample size for this study is sufficient for an initial exploratory study, but this means this study lacks statistical power, as well as limits the generalizability of the findings. In order to validate the findings of the research, there would need to be a larger, randomized sample from the population of automotive garages within Ethiopia. Because the research was confined to Addis Ababa, Ethiopia's socio-economic and climatic context means the city might not be representative of all the urban and rural regions of Ethiopia, nor other countries, thus limiting generalizability. Lastly, the self-reporting nature of the survey and the analysis allows for possible distortions, such as respondents not revealing their actual practices because of social desirability. The findings of the present study could be enriched by a larger and more diverse geographic sample and the use of more direct and objective measures of data collection.

5. Conclusion and Recommendations

5.1. Conclusion

This paper sought to understand the root causes of paint job defects in the automobile spray painting through mixed-methods research, mainly focused on the 4M1E approach (Man, Machine, Material, Method, and Environment). The results clearly show that any one aspect does not dictate paint standards, but rather a combination of shortcomings spread throughout the entire painting environment.

The conclusion remains that a lack of infrastructural control and standardization in the process is the greatest cause of defects. This is most readily evident in the data polarisation, identifying spray booth usage with 58.1% of garages entirely missing this critical environmental control, leaving paints open to dust, contaminants, and uncontrolled humidity. This fundamental error is only made worse due to a wide variety of inconsistent application methods, lack of standardized mixing reference materials, or insufficient flash-off times, resulting in chemical and application issues such as orange-peel and blisters.

There is also a human factor, "Man," that is a central weak point. Formal train-

ing results are polarized, with a majority of technicians being inadequately trained or not trained at all, leading to dependence on variable experience rather than universal best practices. Equipment maintenance (Score: 4.00) While equipment maintenance “Machine” was a relative strength, that doesn’t outweigh other systemic weaknesses. This is strongly corroborated by the outcome of the regression analysis and the fact that the two key characteristics of training and booth use and own skill cover the majority (82.8%) of the variance in paint defect occurrence, strongly supporting the validity of the model.

In other words, the ugly-looking defects such as orange peel, runs/sags, and fish eyes are nothing but a clear reflection of an immature working environment, informal implementation of or no investment in core infrastructure, and a lack of quality systematic control checks.

5.2. Recommendations

An integrative intervening strategy is needed to cut down paint defects significantly, with special attention to the knowledge gaps identified in this study:

5.2.1. For Garage Owners/Management (Short-to-Medium Term)

- Invest in core Infrastructure: I’d start by making the demand to invest in the proper (i.e., require spray booths with controlled flow and filtration and all of the following: This single measure would remove the largest environmental source of pollution.
- Create and implement visual, easy-to-follow standard operating procedures relating to, but not limited to:
- Paint mixing: Make a readable chart of the maximum number of ratio ticks on all of your common name-brand all-purpose laundry stain remover spray bottles for the paint to thinner solution.
- Spray gun setup and maintenance: cleaning intervals & ideal working pressure.
- Flash & dry times: Establish and maintain minimum intercoat recoat intervals as per product data sheets.
- Focused training: “Next steps after informal learning”. Arrangement of systematic practical training in the most common defect triggers (e.g., grip technique, product standard comprehension) and on the relevance of adherence to the new SOPs.

5.2.2. For Policymakers/Industry Associations (Long-Term)

- Introduce certification services—this is similar to the above. You can run some simple certification/rating for auto-body garages where it is mandatory to have minimum infrastructure and techies in the city limits (spray booth, compressor, air dryers)
- Adoption of technology: Create programs that fill the gap between the garage access to low-cost technology like portable humidity gauges, viscosity cups, and entry-level paint thickness gauges with limited budgets, so that they can adapt to data-driven processing.

- Educate: Campaigns that educate the consumer on how their paint infrastructure is worth more than they know, allowing them to ‘vote with their dollars’ and driving market pressure for garages to change.

5.2.3. For Paint Suppliers (Collaborative Role)

Professional support service for garages: whether for sales or after-sales, professional technical support is critical. This features tailored training, a scaled-down mixing manual in the local language, and assistance in case of everyday use issues related to the local environment.

Having addressed these interrelated elements, including such items as infrastructure, consistent methods, training, and industry-wide standards, garages can combat the current cycle of defects, rework, improved quality, enhanced customer satisfaction, and greater economic viability.

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Authors' Contributions

Aregawi Gebremedhin Girmay: Reviewing, collecting data, analyzing, interpreting data, and writing the paper. Professor Wang Zhongmin and Professor Wenping Zhao: Writing, reviewing, editing, commenting, and suggesting. All authors have read and agreed to the published version of the manuscript.

Data Availability

Data are available.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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